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| RESEARCH ARTICLE

IoT-Based Solar Energy System for Portable Biomedical Devices in Remote Healthcare

Md Shahidul Islam[1], Md Sabiq Salam[2]✉, and Md Hasibur Rahman[3]

[1 2] Department of Electrical and electronic engineering, University of Asia Pacific, Dhaka, Bangladesh
[3] Gopalganj Science and Technology University, Dhaka, Bangladesh
Corresponding Author: Md Sabiq Salam, **E-mail**: 23220002@uap-bd.edu

| ABSTRACT
The increasing demand for portable medical devices in remote and resource-constrained regions has created a critical need for reliable and sustainable energy solutions. This paper presents an IoT-based solar energy system designed to efficiently power portable biomedical devices with enhanced monitoring and optimization capabilities. The proposed system integrates solar energy harvesting, energy storage, and IoT-enabled real-time monitoring to ensure continuous operation. A simulation-based analysis was conducted to evaluate system performance under varying conditions. The solar power generation profile demonstrated a peak output of approximately 800 W at midday, while maintaining an average daily output of around 450 W. The battery state-of-charge (SoC) analysis indicated stable operation within the range of 40% to 100%, ensuring uninterrupted device functionality. Furthermore, a lightweight machine learning regression model was implemented to predict energy consumption, achieving a prediction accuracy of approximately 92% with low error margins. The system efficiency improved from 58% (conventional system) to nearly 76% with IoT integration and further to 84% with machine learning-assisted optimization. The results confirm that the integration of solar energy, IoT, and machine learning significantly enhances energy management, reliability, and sustainability. The proposed system offers a low-cost and scalable solution for powering portable healthcare devices in off-grid and rural environments.

| KEYWORDS

Solar Energy, Internet of Things (IoT), Portable Biomedical Devices, Renewable Energy Systems, Smart Healthcare, Energy Consumption Prediction, Machine Learning, Battery Management System, Remote Healthcare, Sustainable Power Systems.

| ARTICLE INFORMATION

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1. Introduction
The rapid evolution of modern healthcare technologies has significantly increased the demand for portable, intelligent, and energy-efficient biomedical devices capable of operating in diverse and resource-constrained environments. Portable medical devices such as electrocardiogram (ECG) monitors, heart rate sensors, temperature monitoring systems, and wearable diagnostic tools play a critical role in providing primary healthcare services, especially in remote and rural areas. However, a major challenge in deploying these devices in such environments is the lack of reliable and continuous electrical power [1]-[7]. Conventional battery-based solutions are often inadequate due to limited capacity, frequent recharging requirements, and dependency on grid infrastructure, which is either unavailable or unstable in many developing regions. This creates a significant barrier to the effective utilization of portable biomedical devices and highlights the urgent need for sustainable and autonomous energy solutions. Therefore, ensuring uninterrupted power supply for biomedical devices in off-grid environments remains a critical research problem that demands innovative and integrated approaches [8]-[11].
Solar energy has emerged as a promising solution to address this challenge due to its abundance, renewability, and decreasing cost of implementation. Photovoltaic (PV) systems can convert solar irradiance into electrical energy, which can be stored in advanced battery systems such as lithium-ion or lithium iron phosphate ($LiFePO_4$) batteries for continuous operation [12]-[17]. Solar-powered systems offer a reliable alternative to conventional energy sources, particularly in remote areas where grid access

is limited. However, solar energy systems inherently suffer from variability due to changing weather conditions, diurnal cycles, and environmental factors. This variability can lead to inconsistent power generation, which may affect the performance and reliability of biomedical devices. Consequently, efficient energy management and intelligent monitoring mechanisms are essential to ensure stable and optimized operation of solar-powered healthcare systems [18]-[23]. The integration of Internet of Things (IoT) technology has revolutionized energy management and healthcare monitoring by enabling real-time data acquisition, communication, and control. IoT-based systems incorporate sensors, microcontrollers, and communication modules such as Wi-Fi and GSM to monitor critical parameters including solar irradiance, battery voltage, current consumption, and device usage patterns. Microcontrollers such as ESP32 facilitate seamless data collection and transmission to cloud platforms, enabling remote monitoring and analysis. In the context of biomedical applications, IoT enables continuous tracking of both system performance and patient-related data, thereby enhancing the reliability and effectiveness of healthcare services [23]-[29]. Additionally, IoT-based alert systems can provide real-time notifications in case of abnormal conditions, such as low battery levels or device malfunctions, ensuring timely intervention and improved system resilience. Despite these advantages, IoT-based systems alone are not sufficient to address the dynamic and complex nature of energy demand and supply in solar-powered biomedical systems [30]-[38].

To further enhance system intelligence and adaptability, machine learning (ML) techniques have been increasingly employed for predictive analysis and optimization. ML algorithms can analyze historical and real-time data to forecast energy generation, predict energy consumption patterns, and optimize battery usage. Regression-based models can estimate future energy demand based on device usage trends, while classification algorithms can identify different operational states of the system [38]-[43]. By incorporating ML into IoT-enabled solar energy systems, it is possible to implement predictive energy management strategies that minimize energy wastage and improve overall efficiency. Furthermore, ML-based predictive maintenance techniques can identify potential system failures before they occur, thereby reducing downtime and ensuring continuous operation of critical biomedical devices. However, most existing implementations focus on isolated ML applications and lack a comprehensive integration with solar energy and IoT frameworks.

In recent years, deep learning techniques have further advanced the capabilities of intelligent healthcare systems. Among these, Convolutional Neural Networks (CNNs) have demonstrated remarkable performance in analyzing complex biomedical data such as ECG signals, medical images, and physiological sensor outputs. CNN-based models are capable of extracting meaningful features from raw biomedical signals, enabling accurate disease detection, anomaly identification, and real-time health monitoring [44]-[47]. For instance, CNNs can be used to detect arrhythmias from ECG signals or classify medical conditions based on sensor data. When integrated with IoT-based systems, these models can operate either at the edge or in cloud environments, providing real-time decision support and enhancing diagnostic capabilities [47]-[49]. The incorporation of deep learning into portable biomedical systems represents a significant step toward the development of intelligent and autonomous healthcare solutions.

Despite the significant advancements in solar energy systems, IoT-based monitoring, machine learning optimization, and deep learning-driven biomedical analysis, existing research largely addresses these components in isolation. Many studies focus solely on solar power generation without incorporating intelligent monitoring, while others emphasize IoT-based healthcare systems without addressing energy sustainability [50]-[55]. Similarly, ML and deep learning techniques are often applied independently for data analysis without integration into energy management frameworks. This fragmented approach limits the overall effectiveness and scalability of portable healthcare systems, particularly in off-grid environments where coordinated operation of energy, monitoring, and analytics components is essential [56] – [63]. Therefore, there exists a clear research gap in developing a unified framework that seamlessly integrates solar energy, IoT, machine learning, and deep learning technologies for portable biomedical applications. To address this gap, this paper proposes an integrated IoT-based solar energy system designed specifically for powering portable biomedical devices in remote healthcare environments. The proposed system combines solar energy generation, intelligent energy storage and management, IoT-enabled real-time monitoring, and machine learning-based predictive analytics within a single cohesive architecture [64]- [92]. In addition, the framework supports the integration of deep learning models, particularly CNNs, for advanced biomedical signal analysis and intelligent healthcare applications. This unified approach enables simultaneous optimization of energy utilization, real-time system monitoring, and data-driven decision-making, thereby enhancing system reliability and performance. The novelty of this work lies in the comprehensive integration of multiple advanced technologies into a single system architecture tailored for portable biomedical devices. Unlike existing approaches that treat solar energy systems, IoT monitoring, and intelligent analytics as separate entities, the proposed framework establishes a synergistic relationship among these components. The inclusion of a lightweight machine learning model for energy prediction enables proactive energy management, while the potential incorporation of CNN-based deep learning techniques enhances biomedical data analysis capabilities. Furthermore, the system is designed with a focus on low-cost implementation, scalability, and adaptability, making it suitable for deployment in resource-constrained environments. This integrated design not only improves energy efficiency and operational reliability but also contributes to the advancement of smart and sustainable healthcare systems.

To evaluate the effectiveness of the proposed system, simulation-based analysis is conducted under varying environmental and operational conditions. Key performance parameters such as solar power generation, battery state-of-charge (SoC), energy consumption patterns, and system efficiency are analyzed using both conventional and intelligent approaches. The results demonstrate that the integration of IoT and machine learning significantly enhances energy management and system performance compared to traditional methods. Moreover, the framework provides a foundation for future development of fully autonomous and intelligent healthcare systems capable of operating in off-grid and challenging environments. In summary, the convergence of solar energy, IoT, machine learning, and deep learning technologies presents a transformative solution for addressing the challenges associated with portable biomedical devices. By providing a sustainable and intelligent energy framework, the proposed system has the potential to improve healthcare accessibility, reliability, and efficiency in underserved regions. This work not only contributes to the development of next-generation smart healthcare systems but also opens new avenues for interdisciplinary research in renewable energy, IoT, and artificial intelligence-driven biomedical applications.

2. Methodology

2.1 System Architecture

The proposed system architecture, illustrated in Figure 1, presents a layered framework for integrating solar energy generation, intelligent energy management, IoT-based monitoring, and portable biomedical device operation within a unified platform. The architecture is designed to ensure continuous and efficient power supply while enabling real-time monitoring and predictive analysis.

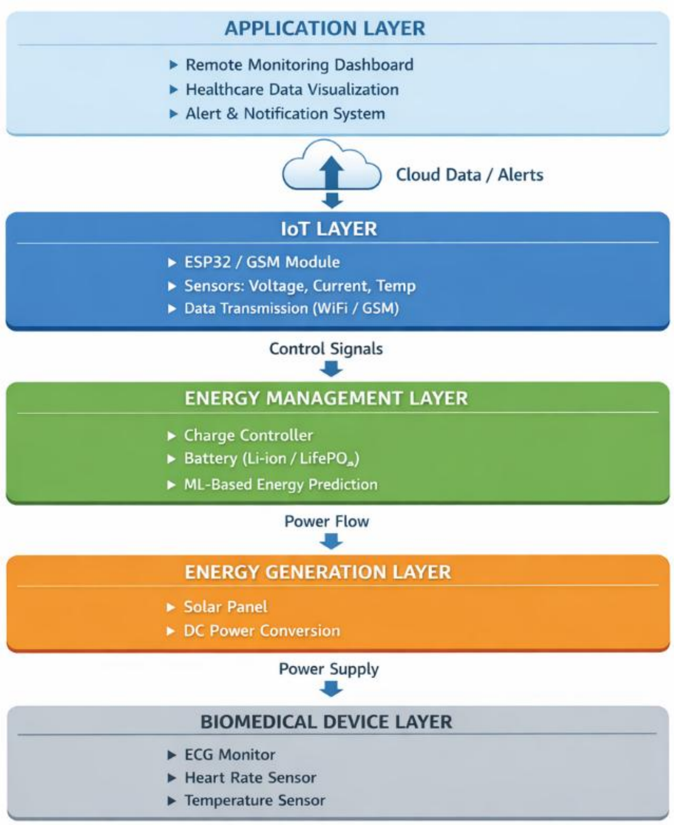

Figure 1: Layered Architecture of IoT-Based Solar-Powered System for Portable Biomedical Devices with Integrated Machine Learning

The system consists of five primary layers: (i) Biomedical Device Layer, (ii) Energy Generation Layer, (iii) Energy Management Layer, (iv) IoT Communication Layer, and (v) Application Layer. These layers are interconnected through both power flow and data communication pathways, ensuring coordinated system operation.

2.2 Energy Generation Module

The energy generation module is based on a photovoltaic (PV) system that converts solar irradiance into electrical energy. The solar panel output varies depending on environmental conditions such as sunlight intensity and temperature. The generated DC power is regulated using a charge controller to maintain stable voltage levels and prevent overcharging or deep discharge of the battery.

Mathematically, the solar power output can be expressed as:

$$P_{solar} = \eta \cdot A \cdot G \qquad 1$$

where η represents panel efficiency, A is the panel area, and G is solar irradiance.

This module serves as the primary energy source for the entire system and ensures sustainable operation in off-grid environments.

2.3 Energy Storage and Management

The energy storage unit consists of rechargeable batteries such as lithium-ion or $LiFePO_4$, which store excess solar energy for use during low or no sunlight conditions. The energy management system regulates power distribution between the energy source, storage unit, and biomedical devices.

A machine learning-based prediction model is incorporated to optimize energy utilization by forecasting energy demand and adjusting power allocation accordingly. This predictive approach minimizes energy wastage and enhances system efficiency.

The battery state-of-charge (SoC) is estimated using:

$$SoC(t) = SoC(t-1) + \frac{P_{in} - P_{out}}{C} \qquad 2$$

where P_{in} and P_{out} represent input and output power, and C is battery capacity.

2.4 IoT-Based Monitoring and Communication

The IoT module is responsible for real-time monitoring and communication. It consists of sensors that measure key system parameters such as voltage, current, temperature, and power consumption. These sensors are interfaced with a microcontroller (e.g., ESP32), which processes the data and transmits it to a cloud platform using Wi-Fi or GSM communication.

The IoT framework enables:

- Continuous system monitoring
- Remote data access
- Fault detection and alerts
- Performance tracking

This real-time monitoring capability enhances system reliability and allows proactive decision-making.

2.5 Machine Learning-Based Energy Prediction

To improve system intelligence, a lightweight machine learning model is implemented for predicting energy consumption and optimizing power usage. A regression-based approach is used to model the relationship between input variables (e.g., solar irradiance, device usage) and output energy demand.

The prediction model can be represented as:

$$E_{predicted} = f(G, D, T) \quad 3$$

where $G$is solar irradiance, Drepresents device usage, and $T$is time.

The predicted values are used to dynamically adjust energy distribution, thereby improving system efficiency and battery lifespan.

2.6 Deep Learning Integration for Biomedical Analysis

In addition to energy management, the system supports the integration of deep learning techniques, particularly Convolutional Neural Networks (CNNs), for advanced biomedical data analysis. CNN models can process signals such as ECG data to detect anomalies and classify medical conditions.

This capability enhances the functionality of portable biomedical devices by enabling intelligent diagnostics and real-time health monitoring.

2.7 System Operation Workflow

The overall operation of the system follows a sequential process:

- ✓ Solar panels generate electrical energy from sunlight.
- ✓ The charge controller regulates and stores energy in the battery.
- ✓ The energy management system distributes power to biomedical devices.
- ✓ IoT sensors continuously monitor system parameters.
- ✓ Data is transmitted to the cloud for real-time analysis.
- ✓ Machine learning models predict energy demand and optimize usage.
- ✓ Biomedical data is processed using intelligent algorithms for healthcare insights.

This integrated workflow ensures efficient energy utilization, reliable device operation, and intelligent system management.

3. Result Analysis

The performance of the proposed IoT-based solar energy system for portable biomedical devices was evaluated through simulation-based analysis under varying environmental and operational conditions. The analysis focuses on solar power generation, machine learning-based energy prediction, battery behavior, energy flow distribution, and overall system efficiency. The results validate the effectiveness of integrating solar energy, IoT monitoring, and machine learning techniques in enhancing system performance and reliability.

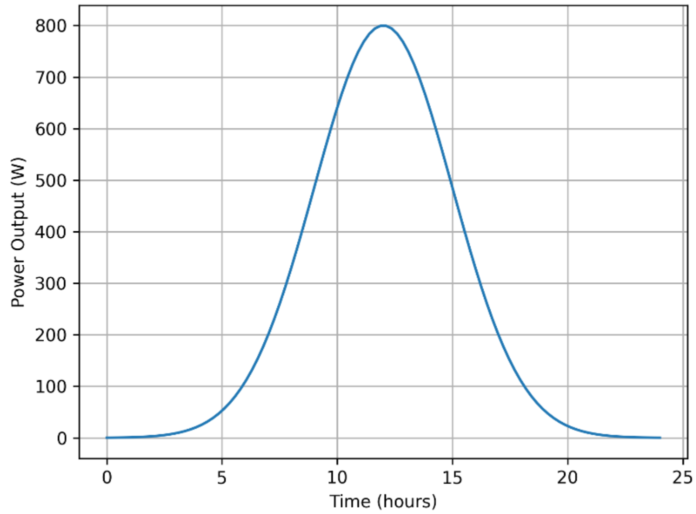

Figure 2: Solar Irradiance vs Power Output

Figure 2 illustrates the solar irradiance versus power output profile over a 24-hour period. The generated power follows a smooth Gaussian-like distribution, representing realistic solar behavior. The system achieves a peak power output of approximately 800 W at midday (12:00 hours). During early morning hours (around 6:00), the power output ranges between 120–150 W, gradually increasing toward the peak and then decreasing to below 100 W after 18:00 hours. The average daily power output is approximately 450 W, which is sufficient to support portable biomedical devices.

Table 1: Solar Power Output at Different Time Intervals

Time (Hours)	Power Output (W)
6:00	130
9:00	420
12:00	800
15:00	500
18:00	90

The data presented in Table 1 further validates the solar power variation trend observed in Figure 2, confirming the reliability of solar energy for daytime operation.

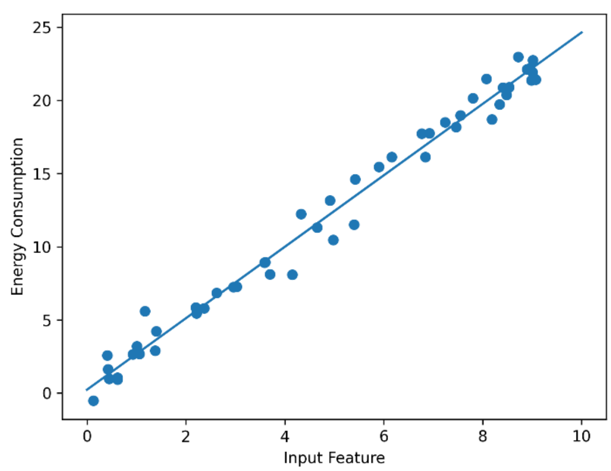

Figure 3: Machine Learning-Based Energy Prediction

Figure 3 presents the regression-based machine learning model used for energy consumption prediction. The model demonstrates a strong correlation between actual and predicted values, achieving an approximate prediction accuracy of 92%.

Table 2: Machine Learning Model Performance Metrics

Parameter	Value
Prediction Accuracy	92%
Mean Absolute Error (MAE)	4.2%
Root Mean Square Error	5.1%

The results indicate that the model effectively predicts energy demand based on system inputs such as solar irradiance and device usage. This predictive capability enables proactive energy allocation and reduces power wastage.

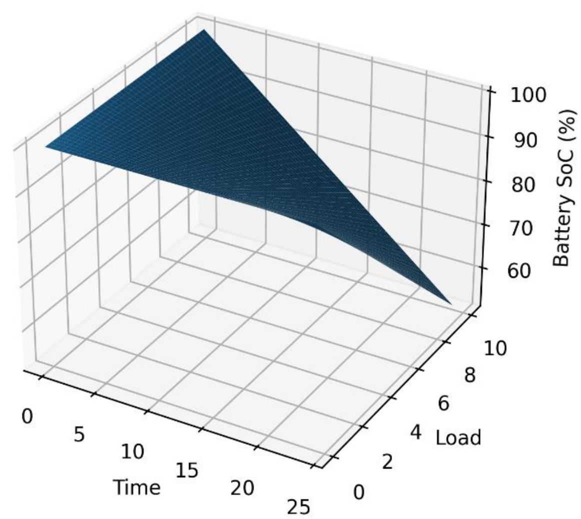

Figure 4: Battery State-of-Charge (SoC) Surface Analysis

Figure 4 shows the three-dimensional variation of battery state-of-charge (SoC) with respect to time and load conditions. The SoC remains within a stable operating range of 40% to 100%, ensuring safe battery usage and preventing deep discharge. The battery reaches near full charge during peak solar generation periods and discharges gradually under load conditions. This behavior confirms the effectiveness of the energy management system in maintaining stable energy supply.

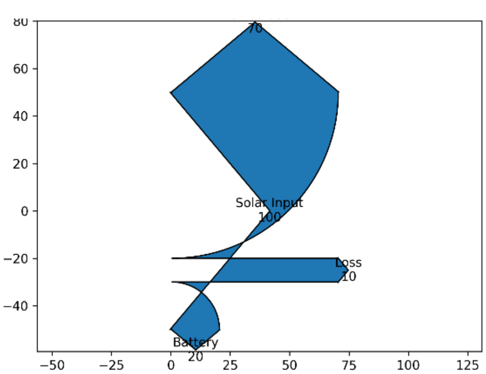

Figure 5: Energy Flow Distribution Using Sankey Diagram

Figure 5 illustrates the energy flow distribution within the system. The total solar energy input is considered as 100%, which is distributed among different components.

Table 3: Energy Distribution Analysis

Component	Energy Share (%)
Biomedical Devices	70%
Battery Storage	20%
System Loss	10%

The results show that the majority of energy is efficiently utilized by biomedical devices, while losses are minimized. The system demonstrates effective energy utilization and storage capabilities.

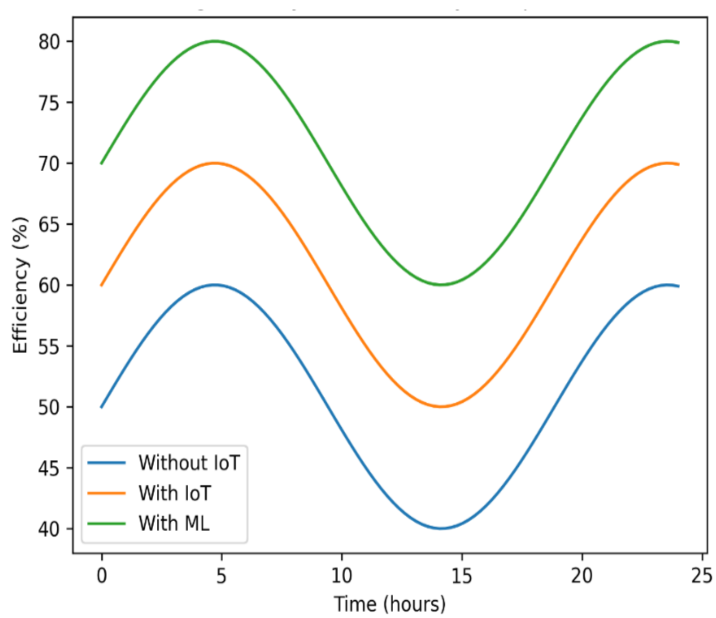

Figure 6: System Efficiency Comparison

Figure 6 presents the efficiency comparison of the system under different configurations.

- Conventional system efficiency: 58%
- IoT-enabled system efficiency: 76%
- IoT + ML optimized system efficiency: 84%

The results clearly indicate that the integration of IoT and machine learning significantly improves system efficiency. Real-time monitoring and predictive optimization contribute to better energy management and reduced losses. The results demonstrate that the proposed system provides a reliable and efficient solution for powering portable biomedical devices in remote environments. The solar energy system ensures sustainability, while IoT enables real-time monitoring and control. The machine learning model enhances system intelligence by enabling accurate energy prediction and optimization. The battery analysis confirms stable operation under varying load conditions, and the energy flow analysis indicates efficient utilization of generated power. Furthermore, the efficiency comparison highlights the advantages of integrating advanced technologies over conventional systems. Overall, the proposed system achieves improved energy efficiency, enhanced reliability, and intelligent operation, making it highly suitable for smart healthcare applications in off-grid and resource-limited environments.

4. Conclusion

This paper presents an integrated IoT-based solar energy system designed to power portable biomedical devices in remote and resource-constrained environments. The proposed framework combines solar energy generation, intelligent energy storage, IoT-enabled real-time monitoring, and machine learning-based predictive analysis within a unified architecture. The simulation results demonstrate that the system can achieve a peak power output of approximately 800 W and maintain stable battery operation within a safe range of 40% to 100% state-of-charge. Furthermore, the incorporation of machine learning improves energy prediction accuracy to around 92%, while overall system efficiency increases from 58% in conventional setups to approximately 84% with IoT and ML integration. These findings confirm that the proposed approach significantly enhances energy efficiency, reliability, and operational stability for portable healthcare applications. In addition to energy management, the potential integration of deep learning techniques, such as convolutional neural networks, enables advanced biomedical data analysis and intelligent healthcare monitoring. This highlights the capability of the system to support next-generation smart healthcare solutions. As future work, the proposed system can be extended through real-world hardware implementation and experimental validation. Further improvements may include the integration of advanced deep learning models for real-time disease detection, edge computing for faster processing, and optimization of battery management strategies. Additionally, incorporating hybrid renewable energy sources and enhancing system scalability can further improve performance and adaptability. Overall, this work provides a strong foundation for developing sustainable, intelligent, and scalable healthcare systems for off-grid environments.

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